LONG-TERM R&D PROJECT SELECTION

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1. Introduction

A major goal of NASA's research and development (R&D) efforts in aeronautics in this year's budget statement is: "to put U.S. industry in position to recapture the 25% of market share lost in the past 25 years" (NASA, 1995). This report interprets that goal to mean that NASA's aeronautics R&D investments will create the appropriate technical environment to stimulate the U.S. aircraft industry and its suppliers to invest in innovative and cost-effective structures and systems that will yield *measurable* economic benefits to the United States. These advanced technologies are ones that firms might not otherwise select for R&D investments using conventional business decision criteria. This report describes a selection mechanism for NASA investments that is based on strict, quantifiable selection criteria. In contrast to the traditional analytical methods, this mechanism explicitly recognizes the value of R&D investments in terms of creating future opportunities in new, untapped technologies.

The value of technological "options" has been repeatedly used as a *qualitative* argument by research administrators in both the private and public sectors to support strategic, long-term research. Unfortunately, traditional financial methods based on estimates of future cash flows totally disregard the value of the choices ("options") provided by R&D programs. These choices reflect opportunities for downstream investment decisions in new technological areas. By expanding the traditional methods of accounting for the value of an R&D program, the mechanism proposed in this report will greatly help in justifying long-term R&D decisions and investments made by the U.S. Government and, in particular, the NASA aeronautics program.

The conventional approach to R&D project selection by a public agency like NASA has many limitations which have been disregarded in most of the applied literature, even though they are by now well understood in the theoretical economic literature. This report will discuss how some of these limitations could be alleviated. And we will propose an innovative approach to R&D program selection (based on stock option pricing theory) which has the potential for justifying risky projects that a conventional approach might automatically eliminate as a candidate investment. The report concludes with suggestions for expansion of this approach into an operational model.

2. The Conventional Approach (NPV) to R&D Project Selection

There have been a number of attempts to create an operational cost benefit analysis (CBA) tool for aeronautical R&D project selection by NASA.[1] The one initiated by Langford (1987) and later extended by Gellman Research Associates (GRA) (1991a, 1991b, 1991c, 1991d, 1992) is one of the most concise efforts to both describe and operationalize such a CBA model. Their approach consists of four steps.

[1] For an earlier attempt see, for example, Williams et al. (1978). Various chapters in Greenberg and Hertzfeld (1992) summarize alternative models and measurement requirements.

- Step 1. Identification of commercial uses. If such uses can be identified, NASA proceeds to step 2. If no commercial uses can be identified, NASA omits step 2 and proceeds to step 3.

- Step 2. CBA from private sector perspective. This reflects CBA from the perspective of an individual private firm. If a firm expects a positive net present value (NPV) it will undertake the project and NASA does not need to get involved. If all firms expect negative NPV, but still commercial uses have been identified (step 1), NASA proceeds to step 3.

- Step 3. CBA from public sector perspective. If social NPV is negative NASA does not get involved. If social NPV is positive NASA undertakes the project (given that private NPV was found to be negative in step 2). Note that GRA believes that this calculation must actually include both the social and private benefits. (Although positive, the latter were not enough to induce private firms to go forward with the project in step 2).

- Step 4. Periodic monitoring. Considering past R&D costs sunk expenses,[2] periodic reevaluation of the project, taking new information as it becomes available, will determine how far along the R&D exercise NASA should remain involved. NASA remains involved until either private NPV turns positive (private sector will continue on their own) or both private and social NPV turn negative (the project is terminated).

The merit of the Langford-GRA model is in the clear articulation of the four successive steps the agency should follow in selecting R&D programs, and the analytical simplicity of the underlying model which rests on the well understood method of net present value analysis. GRA (1991c) explains clearly how to make the model operational by detailing data requirements. GRA(1991d, 1992) applies the methodology to the examples of high-speed civil transport (HSCT) and short takeoff and landing (STOL) technology respectively.

In a traditional fashion, it is argued that the incentives of a firm to undertake an R&D project will be represented by the expected net present value of the after-tax cash-flow generated by the project. This is effectively the calculation in step 2. A firm will undertake the project if the expected NPV above is positive.

$$NPV_i = \sum_{t=0}^{T} CF_{it}/(1+r_i)^t \qquad (2.1)$$

where i denotes the innovating firm, t denotes time, T measures the time elapsed between project start-up and the end of product life cycle, CF is after-tax cash flow, and r is the private discount rate (marginal cost of capital). In addition:

[2] Sunk costs are opportunity costs incurred in the past which are irretreviable and therefore not relevant to current decisions. Public R&D expenditures are frequently treated as sunk costs.

$$CF_i = \left(R_i - K_i - A_i - D_i + SR_i\right)\left(1 - t_{xi}\right) + D_i \qquad (2.2)$$

where R is sales revenues, K is capital costs, A denotes non-capital costs, D is capital depreciation, SR is the scrap value of retired capital, and t_x is the effective marginal tax rate.

In step 3, the social net present value NPV_s (given NASA involvement in the project) is calculated as follows:

$$NPV_s = \sum_{t=0}^{T} CF_{st}/(1 + r_s)^t \qquad (2.3)$$

where the social discount rate r_s is generally different than r_i.[3] The social cash flow is determined to be:

$$\begin{aligned} CF_s = B_s - C_s = {} & \left[\sum_{m=1}^{M} R_{ms} + \sum_{a=1}^{A} R_{as} + LR_s + CS_{as} + EB_s + SC_s\right] - \\ & \left[\sum_{m=1}^{M} \left(K_m + A_m\right)_s + \sum_{a=1}^{A} \left(K_a + A_a\right)_s + K_N + A_N + EC_s\right] \end{aligned} \qquad (2.4)$$

where B_s denotes social benefits, C_s denotes social costs, m references M manufacturing firms (aircraft producers), a references A airlines (aircraft buyers), LR is labor rents (payments above opportunity cost), CS_a is consumer surplus in the airline industry, EB_s is social external benefits, SC is the scrap value of retired capital, N references NASA, EC_s is social external costs, and the rest is as defined previously.[4] If $NPV_i<0$ and $NPV_s>0$, NASA's undertaking of the R&D project is justified.[5] If $NPV_i<0$ and $NPV_s<0$, NASA postpones the project to a later date (to be reexamined).

It is additionally argued that $NPV_i>0$ is not a sufficient condition for ruling out NASA's involvement. NASA may still get involved "if positive incremental net benefits are associated with its participation, even though the project would have been undertaken by the private sector in any event" (GRA, 1991c, p.5-6). It is claimed that, if $NPV_i>0$, the R&D project should also be evaluated from the perspective of the private sector--i.e., not only the perspective of firm i--but without considering participation by NASA. This evaluation will produce NPV_p which should be juxtaposed to the social NPV_s which includes NASA's involvement. If $NPV_s>NPV_p$, NASA's involvement would still be justified even though $NPV_i>0$. NPV_p is obtained as follows:

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[3] $r_s - r_i$ due to risk pooling in the public sector.

[4] The explanation of the individual variables, the economic justification, and the data requirements are explained in GRA (1991c and 1991d).

[5] Note that GRA discussed the case of a one-step R&D project and this is reflected in the variables involved in the calculation of net present values. In later sections we will be concerned with R&D projects where NASA may undertake the preliminary (enabling) stage and the private sector will undertake the development of the final product.

$$NPV_p = \sum_{t=0}^{T} CF_{pt}/(1+r_s)^t \qquad (2.5)$$

where p denotes the private sector. Similarly to the previous exercise it is shown that:

$$CF_p = B_p - C_p = \left[\sum_{m=1}^{M} R_{mp} + \sum_{a=1}^{A} R_{ap} + LR_p + CS_{ap} + EB_p + SC_p\right] - \left[\sum_{m=1}^{M} (K_m + A_m)_p + \sum_{a=1}^{A} (K_a + A_a)_p + EC_p\right] \qquad (2.6)$$

Expression (2.4) contains the same variables as expression (2.6) with the exception of K_N and A_N, the capital and non-capital costs incurred by NASA. GRA expects that these variables may take different values when NASA participates and when it does not participate in the R&D project in question. The reason mentioned is that NASA's participation may speed up the diffusion of technological knowledge among aircraft producers beyond the rate of diffusion if one producer innovated alone. We find this reasoning somewhat dubious, however, since nothing in this model precludes innovation by more than one aircraft manufacturer.[6] In addition, we suspect that the data requirements would make the calculations almost impossible to sustain, even if there was some truth to the argument. Interestingly, the calculation of NPV_p was omitted when the methodology was applied to actual examples (GRA 1991d, 1992).

The sophisticated Langford-GRA model does not avoid the perennial problem of quantifying the necessary variables. Needless to say, obtaining reliable future estimates for the required variables is a difficult task and has constrained considerably the application of cost/benefit methodologies in the past (see, e.g., Bach et al., 1992; Hertzfeld, 1992). This is a generic problem with all such exercises which will not concern us any further in this report.

Instead, we would like to concentrate on two additional problems which have come to haunt all such efforts to select projects with uncertain future outcomes. These relate to:

- The limitations related to the use of possibly inappropriate discount rates which tend to blend time discount factors and risk adjustment factors, create the false impression that project risk follows a simple random walk, and do not account properly for the fact that uncertainty decreases in consecutive stages of R&D as a result of information gathering.

[6] Aircraft industry in the U.S. is dominated by one company, hence the GRA arguments. However, not all innovative R&D will benefit the major market player. Therefore, a more general approach is warranted.

· The dismissal of a very important feature of an R&D investment related to the opportunities it creates for future follow-up investments in a particular technological field. A "strategic," long-term R&D project opens up opportunities (provides an option) for subsequent investment in a potentially profitable technological area. There is a significant value to having such opportunities (option). This value is totally missed by the conventional CBA models like the one reviewed above.

3. Discount Rates

Evaluating long-term strategic investment decisions is an inexact science. By its very nature it involves present decisions about future activities. Future activities are uncertain, and contain unknown risks. Similarly to the Langford-GRA model presented in the previous section, most traditional business models use some form of discounted cash flow analysis to discount future revenue and cost streams from a project and translate them into today's values. By comparing the NPV of a variety of different projects, the "best" decision can be made base on the project with the highest NPV.

This system has a number of flaws, some obvious and some hidden. First, it assumes a constant discount rate into the future--essentially assuming that all forms of risk remain the same five or ten years hence. Second, it assumes that a project has only one outcome--revenue and cost streams--and that alternative paths that the project may take are not considered. Third, it is heavily biased toward large near-term revenues which almost automatically makes longer-term R&D projects appear to be bad investment choices.[7] When inflation is high (such as in the 1980s) the bias toward near-term projects is magnified even more.

These methodologies are even more problematic when applied to public investments. Instead of a revenue stream from a project, public investments may be more focused on maximizing a stream of social benefits which are much more difficult to quantify than corporate revenue flows.

Additionally, in evaluating public expenditures, often the discount rate that is used is one that is imposed upon an evaluator by the OMB. For good political reasons, the OMB sets out the rate that is to be used in all benefit/cost studies. This accomplishes two purposes: 1) agencies cannot unduly weight their results to some partisan purpose by applying either too high or too low a discount rate, and 2) the OMB can better compare across different projects. These reasons may be more appropriate when applied to regulatory matters in government than to R&D decisions. (But, even then, many of the above problems with the methodology remain.)

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[7] It has frequently been pointed out in the management literature that traditional decision making procedures treating R&D as any other investment--thus using similar techniques for justifying the expense--bias decision making against long-term, riskier kinds of R&D projects. Traditional financial justification techniques such as return on investment (ROI) and NPV comparisons of future benefits and costs from an investment tend to discount most heavily the risks involved in projects that hold the greatest promise for allowing firms to come out with significantly different technological positions and allow them to enter new market areas (e.g., Hayes and Abernathy, 1980; Schmitt, 1985; Mitchell and Hamilton, 1988).

A discount rate reflects expectations concerning the future. Using one unvarying discount rate, particularly into the distant future, implies a random walk of interest rates through the years. That is, when the calculations are made today for the whole time frame of the project, the implicit assumption is made that there will be no differences in risk over time. The technical connotation of this assumption is that the risks associated with future cash flow estimates are increasing geometrically with chronological distance from the present.

There are many occasions, however, where risk patterns differ significantly from a random walk (Hodder and Riggs, 1985). A classic case seems to be that of research, engineering, prototype production and testing stages of new aircraft. All these stages provide information about the ultimate cost of production (and probably about potential market conditions as well); each investment stage yields information that reduces the uncertainty over the value of the completed project. The fact that uncertainty decreases in consecutive stages (due to information gathering) should be reflected in differing discount factors for each stage.

Given that accurate fortune telling and crystal ball gazing are not particular strengths of the economics profession, using a set discount rate for the time value of money in the distant future is probably a reasonable assumption, if current market conditions are allowed to dictate the rates (not another government agency). And, since the financial markets routinely value all sorts of investments up to about 30 years hence for long-term bonds, interest rates are available to decision makers.

But this is a simplistic approach to the evaluation of risk. A research and development project is a somewhat unique type of investment--and in the public sector it is even further differentiated from a private sector R&D investment. First, risk can be divided into a number of categories, some more easily estimated than others. They are: 1) technological risk, or the probability of the mission success or that the project will work, 2) market risk, or the probability that the technology will be used in the mission and/or that it will be attractive enough to commercial users that it can be sold at a profit, 3) external risks, or the probability of shocks and changes to the economy, or society that will affect overall financial market risk.

The technological risk is the one that NASA can focus on primarily and vary into the future for R&D projects. Unlike other economic risks, it is likely that the technological risk will *decrease* into the future as the project nears fruition and the unknown aspects of the science and technology become known. NASA personnel are trained to evaluate these types of risks. And, they are also in the best position to be able to break a R&D project into discrete parts. At strategic points in the development of new technologies, risks may undergo sudden changes. These are points that can be evaluated in the methodology we propose herein (stock option model). With variable discount rates applied to the project, some of the biases in R&D project selection can be corrected. These are also the points where the proposed methodology can be employed to value the research in alternative ways--not only as to its initial goal or mission, but also as to its value to others or to other projects or programs.

Finally, most economic analyses assume that the economy is in equilibrium and that all markets and all investors have virtually perfect knowledge. In such as case, using one discount rate might work well. However, the real economy is always adjusting to change. Variations in interest rates not only reflect true variations in risk, but they also reflect imperfect knowledge. Thus, one industry may be perceived as more favorable than another and its firms face a lower interest rate (even if, in fact, that industry is not in a better long-run economic position). Different technologies, different industries, and different projects and programs can be assigned different discount rates. More over, even the same risks may vary according to the degree of options available to the investor. A government agency with large resources can invest in a large portfolio of projects, effectively reducing the overall risk. In contrast, a small company may not have that option and must consider any R&D investment as very risky. That is the second type of modification that we are proposing to consider in this model--one that is flexible enough to build in as many variations in the discount rate as are appropriate for the particular project.

4. R&D to Create and Exercise Options in Future Technology Investments

The previous section mentioned that traditional financial justification techniques have tended to discount most heavily the risks involved in projects that hold the greatest promise for allowing firms to come out with significantly different technological positions and allow them to enter new market areas. It was stressed that this problem also afflicted decision making in the public sector.[8] The project selection and evaluation techniques in current use by the public sector are also biased against longer-term projects because they dismiss the intrinsic value of an initial R&D investment in providing the future choice of getting further involved in a particular technological area or not. Such a choice would not be available if the first R&D investment was never made. The benefit of this choice is lost in the available cost-benefit analyses (Newton and Pearson, 1994).

This may well be a major reason why available econometric techniques have, by and large, not had a significant impact up to now on the R&D selection processes in the public sector. Many a decision maker has felt that there is something more to undertaking risky R&D projects than what is reflected in traditional discounting methods. What is missing is an economic representation of potential and possible future opportunities and directions opened up by an R&D project.[9]

The very important characteristic of certain R&D investments to create opportunities to continue or not continue investing in a particular technological field need not be missed in future project appraisal exercises. Recent economic theory has made considerable progress in accounting for the value of these opportunities. Economists now understand that irreversibility,

[8] Increasingly, the non-military publicly-supported R&D projects are being justified on the basis of tangible returns to the private sector and society at large. This has increased pressures to revert from purely peer review techniques--more appropriate in appraising projects directly related to national defense or the pure enhancement of scientific knowledge--to techniques more akin to appraising economic returns in R&D project selection and evaluation (Vonortas, 1995). The Langford-GRA method is a manifestation of such efforts.

[9] We will, of course, not address in this paper the various political (and personal) reasons that may influence decisions.

uncertainty and the choice of timing affect investment decisions in ways traditional project selection methods omit altogether. Such novel economic ideas should be exploited in ex ante appraisals of uncertain R&D programs by the public sector in general, and NASA Aeronautics in particular.

4.1 R&D to create opportunities

The prerequisite for understanding the value of future choices is the perception of research as a process involving successive stages. Each stage contributes something to the next not only in terms of enabling it -- by providing the necessary technical knowledge -- but also in terms of decreasing the uncertainty involved in it -- by defining the question to be answered more accurately and by adding to the information concerning the operating environment.[10] It is this latter feature that makes longer-term research of particular value.

It should be noted that the research stages we have in mind do not imply anything related to the traditional linear model of innovation.[11] No explicit assumptions are made here on what type of research precedes and what follows. Simply, it is pointed out that certain kinds of knowledge relating to a particular technological field may be a necessary prerequisite in order to embark in more specific (development) research resulting in new or much improved products and production processes. The prerequisite knowledge may be described as generic including "a body of generic understanding about how things work, key variables about affecting performance, the nature of current best practices, major opportunities, currently binding constraints, and promising approaches to pushing these back." (Nelson, 1989, p. 232). Such knowledge has latent public good properties. With the exception of military technologies, the public sector is (and should be) primarily interested in research that enhances generic technological knowledge which assists the private sector to speed up the introduction and commercialization of new or improved products and production techniques.

This conceptualization would be appropriate for describing the content and basic aim of NASA's aeronautics research. NASA's aeronautics R&D complements private sector R&D in cases where social benefits are expected. NASA's aeronautics R&D aims at enabling private sector R&D -- by providing the necessary generic knowledge -- and decreasing the uncertainty involved in it -- by defining the question to be answered more accurately and by adding to the information concerning the operating environment. Hence, NASA's aeronautics R&D is essentially about demonstrating technological opportunities and enabling the private sector to make better choices

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10 This relates to our discussion on the use of appropriate risk-adjusted discount rates for different stages (steps) of the research discussed in the previous section.

11 The traditional linear model of R&D is that funds are first invested in basic research. The knowledge generated from basis research leads to applied work and then to actual development, demonstration, and finally a product that either is sold on the commercial marketplace or is used in government mission work. The modern view is that R&D is a very interactive process--what may start out as basic research can quickly become product oriented, and what is development may actually shed light on more fundamental knowledge. There are many shades of this interaction. The main point is that the products of R&D are not easily predicted in advance. (However, after the fact, there may actually be a valid linear tracing of a product back to fundamental research.)

with respect to such opportunities.[12] Useful methodologies of R&D project selection should certainly address this important feature. Unfortunately, the Langford-GRA methodology is not one of them.

4.2 R&D investment as an option[13]

Any useful methodology of investment resource allocation should address the question: How should a manager (public administrator) facing uncertainty over future technological and market conditions decide whether to invest in a new R&D project?

In trying to deal with this question, the NPV approach makes an implicit, but very strong, assumption. It assumes either that the investment is reversible -- it can be reversed costlessly should technological and market conditions prove to be worse than anticipated -- or that an irreversible investment is a now-or-never proposition -- if the investment is not made now it will never be made. Unfortunately, R&D investment falls in neither of these categories. On one hand, R&D investments are irreversible: there are significant costs associated with terminating a project prematurely.[14] On the other hand, R&D investments can be delayed. There is already significant theoretical literature in economics proving that investment decisions are very much affected by the ability to delay irreversible investments.[15] Necessarily, then, the NPV methodology for allocating R&D resources among competing projects needs to be modified to allow decision makers to account properly for timing, uncertainty and irreversibility.

It has been proposed that there is considerable overlap between "real investment options" and options in financial markets.[16] In particular, it has been suggested that the decision to invest initially in an R&D project with an uncertain outcome is conditional on revisiting the decision sometime in the future. This is similar in its implications to buying a financial call option. A financial call option will permit (but not oblige) the owner to purchase stock at a specified price (exercise price) upon the expiration date agreed in advance. An initial R&D investment will permit (but not oblige) the investor to commit to a particular technological area -- thus, buy the entitlement of the stream of profits from the project -- upon the pre-determined date for

12 It is recognized that a percentage of NASA Aeronautics R&D also has value to military aircraft. This analysis, however, is oriented primarily to the civilian applications of NASA Aeronautics R&D.

13 In this section we draw heavily on the arguments of Dixit and Pindyck (1995) who dealt with investment decisions in the private sector only. See references therein for a complete line-up of current economic thought on the issue of resource commitment in irreversible, uncertain investments.

14 In the public sector, the government may be obliged to pay for shut-down costs.

15 See, for example, Dixit and Pindyck (1994) and the survey article of Pindyck (1991).

16 An early reference is Myers (1977). Subsequently, analogies between "real options" and financial options have been discussed in the context of natural resource valuation such as gold reserves (Brennan and Schwartz, 1986) and oil reserves (Brealey and Myers, 1991) as well as in the more general context of strategic resource allocation in the private sector (Bowman and Hurry, 1993). Analogies with R&D in the private sector have been proposed by Mitchell and Hamilton (1988), Newton and Pearson (1994), and Dixit and Pindyck (1995).

revisiting the initial investment decision.[17] The analogy between the R&D option and the stock option is summarized as follows:

- The cost of the initial R&D project is analogous to the price of the stock option.

- The cost of the future (R&D or other) investment needed in order to capitalize on the results of the initial R&D project when the investment is made is analogous to the exercise price of the stock option.

- The (stream of) returns to the investment subsequent to the initial R&D project is analogous to the value of the stock for the call option.

- The downside risk of an initial R&D project is that the overall cost of the project will be lost if, for whatever reason, the necessary follow-up investments to capitalize on the results are not made. This is analogous to the downside risk for a stock option which, in the case that the option is not exercised, will be the price of the option. In contrast, the downside risk of an investment either in the stock market or elsewhere is that the whole investment may be lost.

- Increased uncertainty decreases the value of an investment (due to risk aversion). In contrast, increased uncertainty--combined with the possibility of higher returns--of an initial R&D project should increase its value if the project is considered as buying an option to a potentially very valuable technology. This is analogous to the effect of uncertainty (volatility) on a stock option: if the volatility of the stock price is zero, the value of the call option is also zero; it is volatility in the stock price that makes the call option valuable (but leaves the downside risk unaffected).

- A longer time framework decreases the (present discounted) value of an investment. However, the value of an R&D option may well increase with time due to the attraction of longer-term, high-opportunity investments (as yet not completely defined) compared to investing short-term with limited application opportunities. This is analogous to the positive effect of time on the value of a financial call option: the further back to the future the agreed expiration date for the option is, the larger the probability of the stock price to exceed a given exercise price.[18]

Thus, it has been claimed that when an investor (NASA aeronautics in our case) commits to an irreversible investment, the investor essentially "exercises" his call option. This, in turn, implies

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17 We discuss "European" options which can be exercised only on the dates of expiration. "American" options, which can also be exercised at any time prior to the agreed expiration date, would imply that an initial R&D investment permits the investor to commit to a particular technological area at any time prior to the pre-determined date for revisiting the initial investment decision. Mitchell and Hamilton (1988) based their discussion on "American" options. While extending the coverage to "American" options would not add significantly to this discussion -- given that realistically none would expect the costs and benefits of on-going R&D projects to be reexamined continuously -- it would introduce considerable complications in operationalizing this approach since there are no comprehensive analytical formulae for American financial options.

18 Note that the last two bullets describe in a sense the arguments of proponents of longer-term, riskier R&D expenditures which tend to be heavily discounted by industry.

that the question of how to go about exploiting future opportunities reverts to a question of how to exercise the corresponding call options optimally. Academics and financial practitioners have studied this problem of financial call options in stock option pricing theory where the value of a stock option has been formally expressed as a function of most parameters involved in options transactions.[19]

4.3 Using options pricing to determine optimal R&D investment

The NPV methodology, then, has many faults. It assumes a fixed scenario with respect to both the conducting of an R&D project and the generation of cash flows during the expected lifetime of the projects' outcome. It largely misses proper accounting of the contingencies, particularly those relevant to delaying the project or abandoning it altogether when the anticipated economic environment proves to have been too optimistic. The NPV methodology compares investing now with not investing at all. In fact, one needs a methodology allowing for a range of possibilities such as investing now, delay and perhaps invest next time period, delay and perhaps invest in the period after next, and so forth. Given that such a methodology would produce a monetary value on the future investment choice provided by R&D, it would allow the manager (public administrator) to rank order competing projects and select the most promising ones for funding.

Two (commonly misunderstood) points need further clarification before proceeding with suggestions of how an options approach to R&D investment can be operationalized. The first point relates to the observation made earlier that the usefulness of an options approach draws on the ability to account explicitly for the choice of investing or not investing in the future. This implies adding something positive on the benefit side of the cost-benefit analysis relating to a particular R&D project -- thus, increasing the possibility that a project proves worthy of undertaking although it is rejected on the grounds of a simple NPV analysis. However, the power of the proposed option approach also rests with the fact that it can accommodate the value of delaying an investment. Investments that are not judged worth undertaking now may become so next time period or the period after next. As said earlier, an important departure of the options approach from the traditional cost-benefit analysis based on NPV is that the former does not treat an investment as a now-or-never proposition. It can thus accommodate temporary delay. When the investor exercises the option, he makes an irreversible investment ("kills" the option). As long as there are some possibilities that the investment would result in a loss, the opportunity to delay the decision -- thus, keep the option alive -- has value.

The second point relates to the observation made earlier concerning the effect of uncertainty on the value of an investment option. It was said that the greater the uncertainty over the potential profitability of an investment, the greater the value of the opportunity and the greater the value

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19 Starting with Black and Scholes (1973) and Merton (1973). See, for example, any leading textbook on corporate finance. The best known references dealing with the technical aspect of the options approach to "real" capital investment are Pindyck (1991) and Dixit and Pindyck (1994).

of waiting (keeping the option alive). This should be extended, however, to reflect the important effects of changes in uncertainty in this system. A small increase in uncertainty can have two effects. On the one hand, it can lead managers (including public administrators) to delay the irreversible investments involving the exercise of the option. On the other hand, it can induce an acceleration of investments that create the option in the first place or reveal additional information -- i.e., the type of aeronautics investments undertaken by NASA.

The option approach to investment can be utilized by government agencies such as NASA to select among alternative R&D programs. The task of the NASA administrator interested in allocating scarce resources among alternative new R&D projects in aeronautics is to determine whether, by undertaking a proposed R&D program, NASA creates a valuable option to a technology which either it or the private sector can exercise at some predetermined future date. In making the go/not go decision at a point in time, the four steps of the Langford-GRA methodology can be retained but must be appropriately modified. The decision-making process concerning a particular R&D project under consideration becomes the following:

Step 1. *Identification of commercial uses*. Delphi methods will be useful in identifying technologies with commercial uses and proposing appropriate areas for NASA aeronautics R&D programs. Given that NASA is a government agency, however, technologies that today have a high potential for commercial applications may not be the only ones to be considered. Delphi procedures may propose technologies that are at a fair distance from the market and yet worthy to be explored.[20] If commercial uses can be identified, NASA proceeds to step 2. If no commercial uses can be identified at present, NASA omits step 2 and proceeds to step 3.

Step 2. *CBA from private sector perspective*.[21] A firm will undertake the specific R&D project if it anticipates a positive value to having the option of investing in the future in the technology involved. NASA, then, drops the R&D project. If no firm has a positive value for the option related to the specific technology, but still commercial uses have been identified in step 1, NASA proceeds to step 3.

Step 3. *CBA from public sector perspective*. If the social value of having the option of future investment in the technology is negative, NASA drops the R&D project. If the social value of the option is positive, and still the private value for the option was found to be negative in step 2, NASA undertakes the project.

Step 4. *Monitoring at predetermined dates*. In order for the options approach to be founded theoretically and for it to be operational, a date for reevaluation of the R&D project (option expiration date) needs to be determined from the start. At the predetermined date, the project will be reexamined, taking in new information as it becomes available. The purpose of this is to

[20] In fact, opening up a future window of opportunity, that is, an option.

[21] The implicit assumption here is that firms also apply the options methodology in choosing among alternative R&D programs. This, of course, may not be true. It is also not at all necessary for our argument. If decision making in the private sector depends on the traditional NPV approach, one simply must substitute "the positive value of creating an option" with "positive NPV" in our discussion.

determine whether NASA should continue the R&D project further or not. NASA terminates the R&D project if either the private value of the option turns positive (continuation of the R&D effort should be taken over by the private sector) or both private and social values of the technology option turn negative.

4.4 An example of the value of the options approach in the public sector[22]

We use an example to demonstrate the value of adopting the options methodology by NASA aeronautics in selecting among alternative R&D programs. We present two iterations of the example to accommodate the cases whereby the private sector does and does not adopt the same methodology in evaluating an initial R&D investment.

It was our intention to keep the example very simple in order to emphasize the main point of this section which is the difference between the traditional NPV and options methodologies in appraising R&D projects *ex ante*. In this illustration we:

- Do not employ a time value discount rate. Discounting would complicate computations but would not add much to the results, given the way the example has been set up.[23] Needless to say, we maintain that a calculation of a real world situation should consider our observations concerning the appropriate discount rates in section III.
- Consider a one-stage R&D project which may be undertaken by NASA. Some of our earlier arguments referred to the value of breaking an R&D project in different stages and apply different discount rates in each. There is nothing inherent in the example to argue against such a procedure. In fact, if discount rates were allowed to decrease during the life time of the project, the results of our example would become stronger. Also, the consideration of a one-stage R&D project for NASA trivializes the procedure involved in monitoring the project (step 4). Future reiterations will relax this assumption.

Step 1.

Suppose that step 1 of the procedure described above determined that it would be of potential value to develop enabling technologies for supersonic civil flight (High-Speed Research program). However, the revenues and costs of future supersonic passenger transport remain highly uncertain. The revenues will depend on a producer's ability to find a market for the transport and the speed of rivals in introducing competing products (if at all). The costs will depend on factors related to the desired characteristics of the plane such as passenger-carrying capability, maximum speed, fuel efficiency, technologies to dampen the sonic boom and so forth.

Suppose also that, as a result of deliberations in step 1, NASA is considering an initial R&D investment of $15 million in supersonic flight. For example, this expense could involve test

[22] We paraphrase an example of the use of the options approach to evaluate ex ante a research project shown in Dixit and Pindyck (1995). Numbers are fictional.

[23] Significant changes would be introduced under the assumption of differential discount rates between the initial R&D project (considered by NASA) and follow-up R&D. We reserve such case examples for future references given that they will need to be based on some theoretical background which we are not prepared to present herein.

flights using the Russian TU-144 supersonic transport to provide data on aerodynamics, flight environment, structure, and handling qualities planned to start in March 1996 (NASA, 1995). It is clearly realized that additional R&D investment resources will be needed to prove the technology (create a prototype of a plane capable of supersonic flight).

Before the initial R&D project under consideration is carried out, the additional expenditures to produce a supersonic transport prototype are anticipated to be one of $40 million, $80 million, and $120 million. Assume that, in the absence of additional information, each of the three additional cost scenarios are considered equally likely: there is a 1/3 (33%) probability of any one happening. Finally, allow for two equally likely revenue scenarios: i.e. a 50% probability that revenues may be either $50 million or $130 million. We keep the example simple by assuming that the time frame is short and the usual discounting can be omitted. The question confronting the NASA administrator is whether the initial R&D investment of $15 million should proceed.

Step 2.

i. Firms use NPV

In step 2, NASA will easily determine that the project is not going to be undertaken by any firm in the private sector. Notice that:

$$NPV_i = E_r - E_c - I \qquad (4.1)$$

where i denotes the innovating firm, E_r is the expected revenue, E_c is the expected additional R&D cost to create the prototype and I is the cost of the initial investment. It can be easily shown that $NPV_i<0$ because:

$$E_r = P_{rl}R_l + P_{rh}R_h = (1/2)x50 + (1/2)x130 = 90 \qquad (4.2)$$

$$E_c = P_{cl}C_l + P_{cm}C_m + P_{ch}C_h = (1/3)x40 + (1/3)x80 + (1/3)x120 = 80$$

where P_{rl} is the probability of the low revenue scenario, R_l is the low revenue, P_{rh} is the probability of the high revenue scenario, R_h is the high revenue, P_{cl} is the probability of the low cost scenario, C_l is the low cost, P_{cm} is the probability of the medium cost scenario, C_m is the medium cost, P_{ch} is the probability of the high cost scenario and C_m is the high cost.

The initial R&D project never takes off in the private sector because the cost ($15m.) is larger than the expected benefit ($10m.). NASA proceeds to step 3.

ii. Firms use options approach

Assume now that a firm considers the initial investment of $15m. as a *sunk cost* enabling it to decrease cost uncertainty. In particular, by providing additional information, the initial R&D investment allows it to buy an option to this technology, that is a right but not an obligation to invest in this technology in the future.

The company analyzes the situation as follows. If at the end of the initial R&D project it is determined that the high-cost scenario will materialize--resulting in E_r-C_h=-30--it will not to exercise the option of continuing the project (abandon project). In that eventuality, its operating profit will be zero. On the other hand, if the initial R&D project indicates that either the middle-cost or the lower-cost scenario materialize--allowing operating profit E_r-C_m=10 and E_r-C_l=50 respectively--the firm will exercise the option and go forward with the additional R&D investment to create a supersonic transport prototype. Considering the probability-weighted average of operating profit across all possible outcomes:

$$\Pi = \Pi_{cl} + \Pi_{cm} + \Pi_{ch} \qquad (4.3)$$

$$= P_{cl}(E_r - C_l) + P_{cm}(E_r - C_m) + P_{ch}(E_r - C_h$$

$$= (1/3)\,x50 + (1/3)\,x10 + 0 = 20$$

where Π is the weighted average operating profit and Π_{cl}, Π_{cm} and Π_{cm} denote the operating profit in the eventualities of low, medium and high cost respectively. Subtracting the sunk cost from Π leaves a surplus of $5m. which makes the initial R&D investment worth while.

The difference between the NPV calculation and the options calculation arises because the option itself is valuable. This value is missed in the NPV calculation.

Step 3.

i. Firms and NASA use NPV approach[24]

As shown above, no single firm will go forward with the initial R&D project on the basis of NPV appraisal. It is immediately realized that, in the absence of any additional benefits to those included in the NPV calculation of individual private firms, NASA would also not get involved and the project would be postponed (or dropped altogether).

[24] We currently know of no firm that has given up ROI of NPV in appraising irreversible investments. An example specific to HSCT is given in Boeing (1989).

The Langford-GRA analysis showed that it is the presence of a "positive incremental social benefit" which will induce NASA to undertake the R&D project in question in lieu of the private sector. In this example, the incremental social benefit should exceed $5 million. That is, the incremental social benefit should exceed the difference between the required initial R&D expenditure ($15 million) and the expected benefit of the aircraft manufacturers (E_r-E_c=$10 million).

What is the nature of the "incremental social benefit"? It consists of elements that are not included in company calculations. These are the potential benefits and costs accruing to society from the existence of an efficient supersonic aircraft beyond those accruing to aircraft manufacturers. As it happens, the experts consulted in step 1 did take into consideration those potential costs and benefits. They certainly mentioned the "strategic value" of building an American supersonic aircraft but did not quantify it. Social costs and benefits involve a myriad factors, including for example (see GRA 1991b, 1991c):

(a) NASA's R&D expenditure.
(b) The overall R&D and production costs and revenues of the aircraft manufacturers.
(c) The capital costs and revenues of airlines that will use the transport.
(d) Labor rents (premiums above labor opportunity cost).
(e) Consumer surplus in the airline industry.
(f) Social external benefits; e.g., noise reduction, technological spillovers to other industries.
(g) Social external costs; e.g., increased noise and air pollution, reduced safety.

The net "incremental social benefit" is the difference of the benefits and costs included in (c) through (g) above. It is these benefits and costs, arguably very difficult to quantify, that need to be assigned explicit value estimates. They should amount to more than $5 million in order for NASA to justify, on the basis of NPV calculations, its involvement in the initial R&D project.

ii. Firms use NPV - NASA uses options approach

A stronger argument in favor of NASA's involvement in the initial R&D project can be built on the basis that, while business firms continue to use NPV analysis to justify their investment in supersonic flight technology, NASA does not. Instead, NASA perceives the value of the option to the particular technology which is created (bought) through the initial outlay of $15 million. Importantly, NASA now justifies its engagement in the project on the grounds of the arguments in step 2, given that the firms will not act on their own. *Notice that, given the selected numbers in this example, a positive incremental social benefit is not necessary in order to prompt NASA's action.*

Of course, the existence of incremental social benefits would make NASA's case stronger. The point, however, is that *one can readily find examples whereby NASA can justify long-term, strategic R&D investments (of the type that create opportunities for the private sector) on the basis of the stock option methodology which would be missed by the simple NPV methodology.*

Step 4.

At a predetermined date, the initial R&D project in supersonic flight is concluded and NASA reevaluates the obtained information. NASA terminates its involvement if either the private value of the option turns positive (private sector takes over the continuation of the R&D effort) or both private and social values of the technology option turn negative.

Two considerations that need to be mentioned here. First, whereas a firm considered the $15 million as a cost before, it will consider it as a benefit (subsidy) after following NASA's undertaking. Second, when, at the completion of NASA's project, a firm will consider whether it should shoulder the remaining expenditure leading to the supersonic transport prototype, the firm will have a better idea of the costs involved. That is, the calculations in step 2 will need to be reevaluated.

Suppose that NASA's flying of the Russian TU-144 gathers information that decreases cost uncertainty. In particular, assume that this information enables one to determine which one of the three cost scenarios related to the production of a prototype will materialize. However, NASA's project does nothing to change market risk. The private sector now reexamines the possibilities of taking over the baton to build the supersonic transport prototype. NASA considers the private sector's decision and acts according to the policy prescription above.

i. Firms use NPV

The private NPV rule determining the willingness of a firm to engage on its own in building the supersonic prototype now becomes:

$$NPV_i = E_r - C \qquad (4.4)$$

It can be easily checked that this equals: (a) -30 when C_h applies; (b) 10 when C_m applies; (c) 50 when C_l applies. If the high-cost scenario materializes, a firm will not undertake the project and will, thus, make zero operating profit. But if either the medium-cost or low-cost scenario materializes, firm i would be willing to engage in the project.

Willing, that is, in the absence of competition. If a rival also engages in an independent project, firm i will consider the resulting loss in future revenues. If, for instance, it is assumed the competitor will be able to shave $20 million off firm i's expected revenues, E_r=70 and the firm would be willing to go ahead only in the case of C_l (NPV_i=30).

ii. Firms use options approach

By considering the decision to build the supersonic transport prototype as a "call option," it can be shown that firms prefer to postpone their immediate engagement even after the successful completion of NASA's initial R&D project has ruled out the high-cost scenario. Suppose that it was determined that the medium-cost scenario will materialize. Even without considering the effects of competition, firms could still decide to wait until they decipher the likely reaction of the market. Waiting will give a firm the choice to go ahead only after it gathered enough information that the high-revenue scenario will materialize. In that case, it would make operating profits equal to R_h-C_m=50. On the other hand, waiting will allow it to avoid the loss-making, low-revenue scenario (R_l-C_m=-30) which implies an operating profit of zero. Since, however, it must make the go now/wait decision ex ante, the relevant calculation is:

$$\Pi^{w} = P_{rl}(R_l - C_m) + P_{rh}(R_h - C_m) = 0 + (1/2)x50 = 25 \qquad (4.6)$$

It is observed that the value obtained by not exercising the option immediately ($25m.)--i.e., wait for market information--is higher than the value of going ahead as soon as NASA's initial project is completed as indicated by the NPV ($10m.). The firm will decide to wait and gauge the market better.

It may be better to wait even if there is danger that a competitor might take part of your expected market. If, as previously, a competitor takes away $20 million of the market, the expected weighted operating profit becomes:

$$\Pi^{w} = P_{rl}(R_l - C_m) + P_{rh}(R_h - C_m) = 0 + (1/2)x30 = 15 \qquad (4.7)$$

which is still larger than the value of going ahead immediately.

The result changes little in the case of the low-cost scenario. Now, if the firm decides to wait until market uncertainty is eliminated, its average expected value ex ante is:

$$\Pi^{w} = P_{rl}(R_l - C_l) + P_{rh}(R_h - C_l) = (1/2)x10 + (1/2)x90 = 50 \qquad (4.8)$$

which is exactly equal to the corresponding NPV. And, after considering competition (subtract $20m. from revenues), its average expected operating profit is:

$$\Pi^{w} = P_{rl}(R_l - C_l) + P_{rh}(R_h - C_l) = 0 + (1/2)x70 = 35 \qquad (4.9)$$

In other words, the firm again prefers to wait.

A final observation must be mentioned here. It was said in the preceding section that, should NASA's initial project determine that the high cost scenario will materialize, firm i would decide to forget about building the supersonic transport altogether if it used the NPV approach. Not so if the firm follows an options approach to project appraisal. The firm now realizes that should the high-revenue scenario play out, it would still make an operating profit (given no competition). It would not make a profit under the low-revenue scenario. Its weighted operating profit ex ante becomes:

$$\Pi^{w} = P_{rl}(R_l - C_h) + P_{rh}(R_h - C_h) = 0 + (1/2)x10 = 5 \qquad (4.10)$$

It is easy to check that firm i would abandon the idea of building the high-cost prototype if competition was anticipated.

Table 1 summarizes private sector reactions--willingness to commit the required additional investment resources to build the supersonic transport prototype--in the wake of NASA's initial R&D project.

Table 1. Private sector reaction following NASA's initial R&D project

Cost	Selection Methodology	Private Choice No Competition	Private Choice With Competition
C_h	NPV	No Go	No Go
	Options	Wait	No Go
C_m	NPV	Go	No Go
	Options	Wait	Wait
C_l	NPV	Go	Go
	Options	Wait	Wait

The only certain case that a firm, using the NPV methodology, will undertake the task of building the supersonic transport prototype immediately is where C_l obtains. In the absence of competition, it will also undertake it if C_m obtains. A firm using the options methodology would rather wait under all cost scenaria.[25]

[25] There are interesting dynamics to be played out if some firms use NPV and others use the options approach for project selection. This, however, is beyond the scope of the present report.

At this point, NASA must decide what it should do next. Clearly, NASA terminates its involvement if firms use the NPV approach for project appraisal and the initial R&D project indicated a low-cost scenario for building the transport prototype. In the case of the medium-cost scenario, the answer depends on the firm's anticipation of competition. If there is room for only one manufacturer of a supersonic transport and a firm steps forward, NASA terminates its involvement.

In all other cases the private sector would either refuse to commit altogether or postpone the effort for the future. In these cases, NASA would have to consider whether the existence of a positive incremental social benefit justified its undertaking of the successive R&D activities toward building the supersonic transport prototype. In our simple example, the magnitude of the incremental social benefit that is sufficient to justify the continuation of NASA's involvement would vary according to the size of the C (cost scenario). Notice here that this example has not considered the potential value of NASA's R&D involvement in terms of allowing the private sector to decrease market uncertainty in the intervening time period (in other words, in terms of buying time for the firms).

All in all, the considerations arising from the options approach to R&D project selection were shown in this example to justify NASA's involvement in the initial (enabling) R&D project and, possibly, in subsequent stages as well. NASA's undertaking seemed to be justified in various occasions which traditional cost/benefit analysis would have a much more difficult time to prove. This depended solely on the proper accounting of the value of longer-term, strategic R&D in terms of opening up opportunities for future investment in new technological areas with potentially substantial returns. This is exactly how public R&D administrators and policy makers have always described the merits of long-term research.[26]

ss to say, these results depend on the specific values chosen for costs, revenues and probabilities in this example. The purpose of the example, however, was to show that one can ate situations supporting the discussion in earlier sections of this

5. Concluding Remarks

Conventional financial methods using estimates of future cash flows for evaluating investments ex ante have tended to suffer from three shortcomings:

- The use of potentially inappropriate discount rates which blend time discount and risk adjustment factors, create the false impression that project risk follows a simple random walk, and do not account properly for the fact that uncertainty decreases in consecutive stages of R&D due to information gathering. "Official" discount rates suggested by the government (OMB) may aggravate the problem by disregarding significant differences in the R&D projects--in terms of both the type of technology and the prevailing industrial organization--sponsored by various agencies.

- Conventional methodologies to appraise R&D investments have tended to disregard the value of the choice, provided by an R&D program, to invest or not to invest later in new areas of technology. Economists now understand that irreversibility, uncertainty and the choice of timing affect investment decisions in ways traditional selection methods omit altogether. Since all three are prevalent characteristics of "strategic," long-term R&D (of the type that NASA aeronautics is interested in), their dismissal in NPV and ROI methodologies may seriously misrepresent the benefit of R&D investments in aeronautics by NASA.

- Obtaining reliable future estimates for the required variables often becomes problematic, especially when industry perceives the particular activity as very uncertain.

This report discussed the first two of these shortcomings. It was argued that one can do better in both respects than current practice. On the one hand, discount rates should appropriately reflect the facts that: (i) various stages in a R&D program are subject to different risks; and (ii) R&D programs in different technological areas are also subject to different risks. There are ways to do this and NASA personnel are trained to evaluate at least the technological risks involved in the various stages of a R&D program. Proper accounting of the economic environment in the industrial sectors expected to be affected by the occasional R&D program should provide additional information about economic risks. The more difficult case is to account for the future value of money, where the interest rates affixed to long-term bonds may be the closest measure.

On the other hand, cost/benefit analysis should reflect the inherent value of longer-term, strategic R&D in terms of opening up opportunities (but not obligations) for future investment in new technological areas with potentially substantial returns. R&D managers in the private sector and public administrators have always described the merits of long-term research on these grounds. It is only recently, however, that the foundations of a methodology capable of capturing what has, up to now, basically been the intuition of practitioners have been formulated. As was the case of the more conventional approaches, the beginnings of this methodology can be traced in finance theory which has, during the last couple of decades, developed measures of the intrinsic value of stock options. It turns out that the basic idea can be applied to "real investments" characterized by irreversibility and considerable uncertainty. Long-term, strategic R&D is a very good candidate.

The incorporation of the proposed changes in government R&D selection methodologies would constitute an important step in facilitating the process of choosing ex ante the best among competing R&D investments characterized by irreversibility, uncertainty and long time periods to fruition. It would also make the selection process more realistic.

Bibliography

Bach, L., P. Cohendet, G. Lambert and M.J. Ledoux (1992) "Measuring and managing spinoffs: The case of the spinoffs generated by ESA programs," in J.S. Greenberg and H.R. Hertzfeld (eds.) *Space Economics*, Washington, D.C.: American Institute of Aeronautics and Astronautics.

Black, F. and M. Scholes (1973) "The pricing of options and corporate liabilities," *Journal of* Political Economy, 81, pp. 637-659.

Boeing (1989) "High-speed civil transport study," NASA Contractor Report 4233, Boeing Commercial Airplanes, New Airplane Development, September.

Bowman, E.H. and D. Hurry (1993) "Strategy through the option lens: An integrated view of resource investments and the incremental choice process," *Academy of Management Review*, 18(4), pp. 760-782.

Brealey, R.A. and S.C. Myers (1991) *Principles of Corporate Finance*, 4th ed., McGraw Hill.

Brennan, M. and E. Schwartz (1986) "A new approach to evaluating natural resource invest ments," in J.M. Stern and D.H. Chew (eds.) *The Revolution in Corporate Finance*, Blackwell.

Dixit, A.K. and R.S. Pindyck (1994) *Investment Under Uncertainty*, Princeton, NJ: Princeton University Press.

__________________________ (1995) "The options approach to capital investment," *Harvard* Business Review, May-June, pp. 105-115.

Gelman Research Associates (1991a) "Review of Langford's technology benefit-cost method," October 15.

________________________ (1991b) "Technology benefits and validation study: Task 3: Review of the economics and technology literature," November 26.

________________________ (1991c) "Technology benefits and validation study: Task 3: Draft methodology report," November 26.

________________________ (1991d) "Application of Langford's method to an HSCT scenario," December 23.

________________________ (1992) "Application of GRA's method to Langford's three case studies: Appendix A: Sensitivity analysis of STOL technology," January 23.

Greenberg, J.S. and H.R. Hertzfeld (eds.) (1992) *Space Economics*, Washington, D.C.: American Institute of Aeronautics and Astronautics.

Hayes, R.H. and W. Abernathy (1980) "Managing our way to economic decline," *Harvard* Business Review, July-August.

Hertzfeld, H.R. (1992) "Measuring returns to space research and development," in J.S. Greenberg and H.R. Hertzfeld (eds.) *Space Economics*, Washington, D.C.: American Institute of Aeronautics and Astronautics.

Hodder, J.E. and H.E. Riggs (1985) "Pitfalls in evaluating risky projects," *Harvard Business* Review, 85(1), pp. 128-135.

Langford, John S. III (1987) "Federal Investment in Aeronautical Research and Development: Analyzing the NASA Experience," Ph.D. Dissertation, Massachusetts Institute of Technology.

Merton, R. (1973) "Theory of rational option pricing," *Bell Journal of Economics and Manage-*ment Science, 4, pp. 141-183.

Mitchell, G.R. and W.F. Hamilton (1988) "Managing R&D as a strategic option," *Research-*Technology Management, 31(3), pp. 15-24.

Myers, S.C. (1977) "Determinants of corporate borrowing," *Journal of Financial Economics*, 5, pp. 147-176.

National Aeronautics and Space Administration (1995) "Fact Sheet on Aeronautics: NASA FY1996 Budget Request Briefing Package," Washington, D.C.: NASA Headquarters, January.

Newton, D.P. and A.W. Pearson (1994) "Application of option pricing theory to R&D," *R&D* Management, 24(1), pp. 83-89.

Pindyck, R.S. (1991) "Irreversibility, Uncertainty, and Investment," *Journal of Economic* Literature, XXIX, pp. 1110-1148.

Schmitt, R.W. (1985) "Successful corporate R&D," *Harvard Business Review*, May-June.

Vonortas, N.S. (1995) "New directions for US science and technology policy: The view from the R&D assessment front," *Science and Public Policy*, 22(1), pp. 19-28.

Williams, L.J., H.H. Roy and J.L. Anderson (1978) "A method for the analysis of the research and costs for aeronautical research and technology," Ames Research Center, National Aeronautics and Space Administration.